RD-23,530

A REDUCED-POWER GPS-BASED SYSTEM
FOR TRACKING MULTIPLE OBJECTS
FROM A CENTRAL LOCATION

add CIS

Field of the Invention

5   This invention relates to object tracking systems used to locate and track multiple terrestrial (including water-based) objects and, more particularly, to power efficient object tracking systems based upon information obtained from 10   satellites.

Background of the Invention

The tracking and location of assets such as railcars, shipping or cargo containers, trucks, truck trailers, automobiles, etc. can be highly advantageous 15   in commerce. Precise tracking of such vehicles and objects can facilitate their being allocated and positioned in an efficient manner, and can provide for immediate, accurate localization of lost, delayed or damaged assets. The space-based global positioning 20   system (GPS) implemented by the United States Department of Defense constitutes a convenient instrumentality for determining geographical position in real time.

The GPS is a multiple satellite-based radio 25   positioning system in which each satellite transmits data that allows precise measurement of the distance from selected ones of the GPS satellites to the antenna of a user's receiver so as to enable the user to compute position, velocity and time parameters 30   through known triangulation techniques. The signals provided by the GPS can be received both globally and continuously.

The GPS comprises three major segments known as the space, control and user segments. The space segment consists of 21 operational satellites and three spare satellites. The satellites are positioned

5   in a constellation such that typically seven satellites, but a minimum of four, are observable by a user anywhere on or near the earth's surface. Each satellite transmits signals on two frequencies known as L1 (1575.42 MHz) and L2 (1227.6 MHz), using spread

10   spectrum techniques that employ two types of spreading functions.

C/A (or coarse/acquisition code) and P (or precise) pseudo random noise (PRN) codes are transmitted on frequency L1, and P code only is

15   transmitted on frequency L2. The C/A is available to any user, military or civilian, but the P code is only available to authorized military and civilian users. Both P and C/A codes contain data that enable a receiver to determine the range between a satellite

20   and the user.

Superimposed on both the P and C/A codes is a navigation (NAV) message. A NAV message contains the GPS signal transmission time; a handover word used in connection with the transition from C/A to P code

25   tracking; ephemeris data for the particular satellites being tracked; and almanac data for all of the satellites in the constellation, including information regarding satellite health, coefficients for the ionospheric delay model for C/A code users, and

30   coefficients used to calculate universal coordinated time (UCT).

The control segment comprises a master control station (MCS) and a number of monitor stations. The monitor stations passively track all GPS satellites in

35   view, collecting ranging data and satellite clock data

3

from each satellite. This information is passed on to the MCS where the satellite's future ephemeris and clock drift are predicted. Updated ephemeris and clock data are uploaded to each satellite for
5   retransmission in each satellite's navigation message. The purpose of the control segment is to ensure that the information transmitted from the satellites is as accurate as possible.

The GPS is intended to be used in a wide variety
10   of applications, including space, air, sea and land vehicle navigation, precise positioning, time transfer, altitude referencing and surveying. A typical GPS receiver comprises a number of subsystems, including an antenna assembly, an RF (radio frequency)
15   assembly, and a GPS processor assembly. The antenna assembly receives the L-band GPS signal and amplifies it prior to insertion into the RF assembly. A significant factor affecting accuracy of the computed position, velocity or time parameters is the
20   positional geometry of the satellite selected for measurement of ranges. Generally, a best position solution is obtained using satellites having wide angles of separation. Considerable emphasis has therefore been placed on designing antenna systems to
25   receive, with uniform gain, signals from any point on the hemisphere.

The RF assembly mixes the L-band GPS signal down to a convenient IF (intermediate frequency) signal. Using various known techniques, the PRN code
30   modulating the L-band signal is tracked through code-correlation at the receiver. This provides the processing gain needed to achieve a signal-to-noise ratio (SNR) sufficient for demodulating the navigation data and signal transmission time. The Doppler shift
35   of the received L-band signal is also measured through

a carrier tracking loop. The code correlation and carrier tracking function can be performed using either analog or digital signal processing.

5   By differencing the signal transmission time with the time of reception, as determined by the clock of the receiver, the pseudo range between the receiver and the satellite being tracked may be determined. The pseudo range includes both the range to the satellite and the offset of the clock from the GPS

10   master time reference. The pseudo range and Doppler measurements (and the navigation data) from four satellites are used to compute a three dimensional position and velocity fix, which calibrates the receiver's clock offset and provides an indication of

15   GPS time.

      In some known receivers, the receiver processor controller (RPC) functions are performed using a computer separate from that on which the navigation functions are performed. In other known receivers,

20   both types of functions are performed by a single computer. The RPC processing and memory functions performed by a typical GPS receiver include monitoring channel status and control, signal acquisition and reacquisition, code and carrier tracking loops,

25   computing pseudo range (PR) and delta range (DR) measurements, determining data edge timing, acquisition and storage of almanac and ephemeris data broadcast by the satellites, processor control and timing, address and command decoding, timed interrupt

30   generation, interrupt acknowledgment control and GPS timing.

      U.S. Patent No. 5,225,842 describes an apparatus and method for computing the position and velocity of multiple low cost vehicle-mounted sensors, monitored

35   and tracked by a central control station. The

receiver processor functions are physically separated from the navigation functions and the low rate data interfaces provided between the computers that perform these functions, thus achieving cost saving in the GPS
5 sensor that is employed on board each vehicle.

One type of known GPS receiver is described in U.S. Patent No. 4,114,155, wherein the position of a receiver responsive to C/A signals derived from multiple, orbiting spacecrafts is determined to an
10 accuracy better than 300 meters. Each of the C/A signals has the same carrier frequency and a different, predetermined Gold code sequence that normally prevents position determination from being more accurate than to within 300 meters. C/A signals
15 transmitted to the receiver are separately detected by cross-correlating received Gold code sequences with plural locally derived Gold code sequences. Four of the detected C/A signals are combined to compute receiver position to an accuracy of 300 meters. To
20 determine receiver position to an accuracy better than 300 meters, the relative phase of internally-derived Gold code sequences is varied over the interval of one chip (i.e., pulse) of each sequence, to derive second cross-correlation values indicative of received and
25 locally-derived Gold code sequences.

The basic approach followed most recently is to receive and process the signals from several of the GPS satellites in order to determine range to each satellite (and relative velocity). With perfect
30 knowledge of range to only three of the GPS satellites, exact receiver position can be determined from the intersection of the three "spheres" induced by the known satellite positions and the derived receiver ranges. With receiver noise and imperfect
35 knowledge of satellite positions, the receiver-

satellite ranges can only be estimated. Typically, errors from receiver noise are reduced by (effectively) averaging many range calculations.

In the above most recent approach, the range
5   from a particular satellite is estimated by reading a time stamp from the satellite's data stream (the transmission instant), subtracting this from the reception time, and multiplying the time difference by the speed of light. Any error in satellite and
10 receiver clock synchronization leads to proportional range errors. Because the same clock is used in receiving from all satellites, there is only one unknown receiver clock "bias". By using a fourth (or more) satellite, the clock bias and ranges can be
15 jointly estimated.

At the receiver, the reception time is determined by performing a cross-correlation of the received data with a local replica of the known satellite Gold code, and noting the time of a chosen
20 correlation peak, and its position relative to the time stamp. The satellite signal structures use Code Division Multiple Access (CDMA) so that the above cross correlation is part of the standard GPS receiver processing.

25 The above-described system that follows the most recent basic approach assumes that each receiver must determine its own position. In the system of the invention, there is a central facility or station that needs the receiver positions and can communicate with
30 the receivers. Each tracked object (e.g., a railcar) carries a GPS-based receiver that processes data from several of the visible GPS satellites. However, the full position determination is not made at the railcar. Instead, only partial processing is done at
35 the railcar and intermediate results are transmitted

to the central station. The forms of both the partial
processing and intermediate results are chosen to
minimize the complexity and energy requirements at the
railcars.

5   The standard GPS system requires that the
transmit-time stamps, satellite ephemeris and other
correction data be decoded from each satellite's data
stream at the tracked object. The receiver is thus
required to process data from each satellite long
10   enough (between six and 150 seconds) to synchronize
with, and decode, these data. This consumes
significant power.

Summary of the Invention

       Briefly, in accordance with a preferred
15   embodiment of the invention, a method for identifying
location of an asset or object to be tracked comprises
measuring data related to propagation time differences
between signals transmitted from a plurality of
satellites and received at the object to be tracked,
20   transmitting the data to a central station, and
calculating, at the central station, the location of
the object to be tracked based upon the transmitted
data. The data received at the object to be tracked
may include data identifying a respective associated
25   satellite by, for example, a satellite identification
number, such that the step of calculating the location
of the object to be tracked is thereupon based further
upon the satellite identification numbers.

       In another preferred embodiment, a reduced-power
30   GPS-based system for tracking location of an asset or
object from a central location comprises a central
station at the central location, and an object to be
tracked which includes means for receiving signals
from at least four GPS satellites, first processor
35   means for processing data from the receiver means

propagation time differences for the signals, and transmission means for transmitting the processed data to the central station. Second processor means situated at the central station determine location of

5   the object based upon the data received from the transmission means.

In still another preferred embodiment, a reduced-power GPS-based system for tracking multiple objects from a central location comprises a central

10   station at the central location, and a plurality of objects to be tracked. Each of the objects includes receiver means containing an antenna for receiving signals including data related to the propagation time differences of the signals from at least four GPS

15   satellites, first processor means for calculating a receiver code word phase for each of the satellites based upon the signals received by the receiver means, and transmission means for transmitting the code word phase to the central station. Second processor means

20   are provided at the central station for determining the signal propagation times between the plurality of satellites and each of the tracked objects based on the receiver code word phase transmitted by the respective object and for determining from the signal

25   propagation times the location of each respective one of the objects.

In another preferred embodiment, a reduced-power GPS-based system for tracking location of multiple objects from a central location comprises a central

30   station at the central location, and an object to be tracked which includes means for receiving signals including data related to propagation time differences of said signals from at least four GPS satellites, first processor means for calculating a receiver code-

35   time offset for each of the satellite signals and for

determining the receiver code period for each signal, and for determining identification numbers of the at least four GPS satellites, and transmission means for transmitting the receiver code-time offsets, code

5   periods, and identification numbers to the central station. Second processor means at the central station determine the signal propagation times between the plurality of satellites and the tracked object and determine location of the object based upon the

10   receiver code-time offsets, code period, and satellite identification numbers transmitted by the transmission means.

In still a further preferred embodiment, a reduced-power GPS-based system for tracking location

15   of an object from a central location comprises a central station at the central location, and an object to be tracked which includes means for receiving transmission signals from at least four GPS satellites, first processor means for calculating a

20   receiver bit phase for each of the satellite signals based upon the signals received by the receiver means, means for keeping track of time at the object, and transmission means for transmitting the bit phase signals and time signals to the central station.

25   Second processor means are provided at the central station for determining the signal propagation times between the plurality of satellites and the object and for determining location of the object based upon the bit phase and time signals transmitted by the

30   transmission means.

Utilizing the present invention, power consumption and calculation complexity at the tracked object are reduced relative to that for a standard GPS receiver. Arrival time differences between satellite

35   signals are measured at the tracked object and this

information is relayed to the central station via the separate communications link. Satellite data streams need not be decoded at the tracked object.

5 The central station thereby necessarily determines the location of the object to be tracked. Because the receiver front end and data processor use significant power only when processing, the receiver power can be dramatically reduced by being "active" only long enough to get accurate time-difference
10 measurements. This can be less than one second and requires no GPS data-frame synchronization because of the nature of the signals. For example, assuming that the tracked object is a railcar, new railcar locations typically are needed only as frequently as 15 minutes.
15 Thus the receiver energy used is reduced in direct proportion to the reduction of "active" receiver time. Moreover, receiver complexity and cost can be reduced by replacing the advanced microprocessor employed in current GPS receivers with a simpler one that is
20 matched to the arrival-time differencing tasks.

In accordance with the invention, one object is is to provide a GPS-based asset tracking system in which processing is performed at a location remote from the tracked assets and based upon specific
25 recognizable variables.

Another object is to provide a GPS-based asset tracking system which requires minimal energy at the tracked assets.

30 **Brief Description of the Figures**

The features of the invention believed to be novel are set forth in the appended claims. The invention, however, together with further objects and advantages thereof, may best be understood by

reference to the following description taken in conjunction with the accompanying drawing(s) in which:

Figure 1 is a block diagram of a remote tracking system in accordance with the present invention;

5   Figure 1A is a block diagram of a railcar tracking unit on an object to be tracked in accordance with the invention;

Figure 1B is a block diagram of the transmitter at the central station of the remote tracking system
10   of the invention;

Figure 2 illustrates the long time-scale data frame relationship between a GPS standard time mark and two satellite data frames in accordance with the present invention;

15   Figure 3 illustrates a typical Gold-code correlation output signal on a short time scale when the proper code replica is used at the local station receiver;

Figure 4 illustrates the time delay
20   relationships of the transmitted and received signals;

Figure 5 illustrates a plurality of intersecting time-difference solution regions on the surface of the earth;

Figure 6 illustrates tracked object message
25   timing diagrams in accordance with the present invention;

Figure 7, illustrates tracked object location-dependent communication delay; and

Figure 8 is a block diagram of a system for
30   evaluating GPS algorithms in accordance with the present invention.

Detailed Description

The present invention is directed to a system and method for reducing the power and complexity

requirements of a local GPS receiver, which can be carried by a railcar, by effectively requiring only measurement of arrival-time differences between a plurality of GPS satellite signals. Data related to
5 these time differences are transmitted to a central station where the majority of calculations required to determine the receiver (railcar) location are performed. In the preferred embodiments, a standard CDMA receiver is employed with radio
10 frequency/intermediate frequency (RF/IF) front end and Gold-code cross correlators.

In Figure 1, the invention is shown as comprising a plurality of GPS satellites 12, an object to be tracked, such as a railcar carrying a tracking
15 unit 14, and a central station 16. Although the invention is herein described in the context of a railcar, the teachings of the invention are applicable to a variety of objects which may be tracked by a GPS or satellite-based system. With respect to the GPS
20 signal format, accurate timing of GPS signals is critical and is monitored by central station 16.

Each satellite 12 includes its own set of clock correction parameters within its data stream. These allow a receiver to ascertain the absolute
25 transmission timing for each satellite with respect to a common GPS standard time. A particular satellite's clock may drift relative to those of other satellites. The GPS system control monitors these offsets and periodically includes them in the satellite's data
30 stream. The clock time offsets are not needed at the individual receivers and can be determined at central station 16 by utilizing a standard GPS receiver there or at a remotely controlled site.

As shown in Figure 1A, railcar tracking unit 14
35 is actually comprised of a railcar receiver 2

13

responsive to the signals from GPS satellites 12, a processor 3, and a transmitter 4. The received signals are processed in processor 3 to ascertain and utilize propagation time differences among the signals
5   received from GPS satellites 12. The processed signals are furnished to transmitter 4 from whence they are transmitted, as reduced order parameters, to central station 16.

As shown in Figure 1B, central station 16
10   includes a receiver 7 responsive to signals from transmitter 4 of tracking unit 14 (Figure 1A) and a processor 8 responsive to receiver 7 for determining location of tracking unit 14.

In the long time scale data frame shown in
15   Figure 2, a_i is the frame time offset for satellite i. A value $a_j - a_i$ is the time offset between transmitted signals from two satellites, i and j.

A Gold-code correlator output waveform $r_i(t)$ for satellite i is illustrated in Figure 3 from the
20   perspective of the railcar receiver. Each correlation-peak location respectively marks the beginning of a new Gold code cycle in the received waveform. Each Gold code cycle is 1ms long and comprises 1023 binary Gold code "chips". Furthermore,
25   there are 20 code cycles for each encoded navigation data bit. Figure 3 also illustrates, by a dotted line, a typical bit-boundary position.

With respect to a particular time t_R at a railcar receiver, the receiver code-time offset for
30   satellite i is γ_i. The receiver code-time offset is the time elapsed to a time t_R from the beginning of the code word (cycle) in which t_R falls. Similarly, the receiver bit-time offset β_i is the time elapsed to time t_R from the beginning of the bit in which t_R
35   falls. The satellite-railcar radial velocity

component varies for different satellites and this results in a relative waveform expansion or compression (Doppler) at the railcar. Thus the observed code and bit periods are satellite dependent.

5   The code and bit periods observed at the railcar for satellite i are designated as T_i^C and T_i^B, respectively.

Frequently, the railcar receiver will use satellite signals that are not visible from (i.e.,

10   cannot be received by) the central station. This presents no problem because the satellite clocks drift slowly (less than five nanoseconds error per hour). If, at the railcar receiver, time differences are calculated using a satellite that is not visible at

15   the central station, then, at the central station, the last calculated clock offset for that satellite can be used (or extrapolated, based on past drift rate) until that satellite is again visible. As an alternative, central station 16 (Figure 1) could communicate with

20   standard GPS receivers strategically situated to guarantee satellite visibility.

A key feature of the present invention is the provision of a method for determining location of the object (here, a railcar) to be tracked. In a first

25   method ("method 1"), the object's location is accurately determined from propagation time differences between at least five satellites' signals received at the tracked object. This method requires no measurement of time at the tracked object. The

30   propagation time difference between signals from satellites i and j is defined as $\Delta_{ij} = \tau_j - \tau_i$, where τ_i is the signal propagation time from satellite i to the railcar. These propagation times are not directly measured at the receiver but are calculated from

35   received code word or bit phases, as described below

(see equations 8 and 9). The satellite-railcar ranges and propagation time differences are related by the equation

$$R_i(t, t - \tau_i) - R_1(t, t - \tau_1) = C\Delta_{1i}(t), \qquad (1)$$

5   or:

$$R_2(t, t - \tau_2) - R_1(t, t - \tau_1) = C\Delta_{12}(t)$$

$$R_3(t, t - \tau_3) - R_1(t, t - \tau_1) = C\Delta_{13}(t)$$

$$R_4(t, t - \tau_4) - R_1(t, t - \tau_1) = C\Delta_{14}(t)$$

$$R_5(t, t - \tau_5) - R_1(t, t - \tau_1) = C\Delta_{15}(t)$$

10   where $R_i(\ )$ is a function of the parameters in its argument and is discussed below. In equation (1), t is the common time at which the signals are measured at the receiver, C is the speed of light, and

$$R_i(t, t-\tau_i) = \qquad (2)$$
$$[(x(t)-x_i(t-\tau_i))^2+(y(t)-y_i(t-\tau_i))^2+(z(t)-z_i(t-\tau_i))^2]^{1/2}$$

15

is the range from the i'th satellite to the railcar receiver. Also, x_i, y_i and z_i are time-dependent coordinates for satellite i and are specified by the satellite's ephemeris equations. For satellite i, the

20   signal received at time $t = t_R$ was transmitted at time $t_R - \tau_i$, which is now defined as t_i^T. Time t_R is identical for all of the satellites. Furthermore, the propagation times are related by

$$\tau_i = \tau_1 + \Delta_{1i}. \qquad (3)$$

25   For any particular measurement time $t = t_R$, equation (1) can be rewritten as

$$R_2\left(x,y,z,t_1^T - \Delta_{12}\right) - R_1\left(x,y,z,t_1^T\right) = C\Delta_{12} \qquad (4)$$

$$R_3\left(x,y,z,t_1^T - \Delta_{13}\right) - R_1\left(x,y,z,t_1^T\right) = C\Delta_{13}$$

$$R_4\left(x,y,z,t_1^T - \Delta_{14}\right) - R_1\left(x,y,z,t_1^T\right) = C\Delta_{14}$$

$$R_5\left(x,y,z,t_1^T-\Delta_{15}\right)-R_1\left(x,y,z,t_1^T\right)=C\Delta_{15} \quad .$$

The corresponding satellite transmission times are needed to properly determine the satellite locations needed in equation (2). From equations (2), (3) and
5 (4), the object coordinates x, y, z and the transmission time t_1^T form the only unknowns. Yet the time delay differences in equation (1) do not have to be calculated with reference to satellite (1); i.e., any satellite pairing will be satisfactory as long as
10 the four equations in (1) utilize unique pairings.

Using these simultaneous equations at central station 16 (Figure 1), four time delay differences determine a point at the intersection of four hyperbolic sheets in three dimensional space as well
15 as the unknown transmit time, t_1^T. The other satellite transmission times t_2^T, t_3^T, t_4^T, and t_5^T are then found from the equation:

$$t_i^T=t_1^T-\Delta_{1i} \quad . \tag{5}$$

The resultant values are utilized to determine
20 the satellite locations needed in equation (2). The nonlinear equations (4) are readily solved with standard techniques using iteration. It is not necessary that time t_R be measured at the railcar receiver. This value can be found, if desired, at the
25 central station from the equation:

$$t_R=t_1^T+R_1/C \quad . \tag{6}$$

In the present invention, the propagation time differences Δ_{ij} are not directly measured at the railcar receiver. Instead, only the code or bit
30 phases associated with reception time t_R are measured, and these data, or their differences including the

satellite identifications, are transmitted to the central station. This permits the railcar receiver to focus only on cross correlation and to operate long enough to get a sufficient SNR (Signal-to-Noise Ratio)

5 through averaging. In general, the averaging times are so brief that any Doppler shifts can be considered as constants. Thus the bit and code periods are constant during these periods. Railcar locations can be determined at the central station by calculating

10 the true differential delays from the measured phases, as described below, and using them in equations (1) through (5).

In determining the propagation time difference between two satellite signals, it is assumed that the

15 Doppler shift is constant locally, *i.e.*, that the satellite-railcar propagation delay changes linearly with time. Using this assumption, a particular relative position in a received code word or data-bit cycle corresponds to the same relative position in the

20 associated transmitted code word or data-bit cycle. From the previous definitions, and as shown in Figure 4, for each satellite *i*, *j*, etc.,

$$t_R = t_i^s + T^c(m_i + \mu_i) + \tau_i . \tag{7}$$

Pursuant to equation (7), t_i^s is the time when the

25 start of a currently received frame was transmitted, m_i is the integer number of code periods between time t_R and the beginning of the received data frame, and μ_i is the receiver code word phase at time t_R and is defined as

30
$$\mu_i = \gamma_i / T_i^C \tag{8}$$

where γ_i is the receiver code-time offset at the receiver, and T_i^C is the code period (at time t_R) in the received data frame. T^C is the common code period

at all transmitters. Because the Doppler shift is
constant, it is true that

$$\varepsilon_i/T^C = \gamma_i/T_i^C \qquad\qquad (9)$$

so the relative code word phase in the transmitted
waveform at time $t_R - \tau_i$ is equal to μ_i that was
measured at the receiver at time t_R. From equation
(7), the propagation time difference between signals
from satellites i and j is

$$\Delta_{ij} = \tau_j - \tau_i = a_j - a_i + T^C(m_i - m_j) + T^C(\mu_i - \mu_j) \qquad (10)$$

which utilizes the equation $t_i^S = t_{GPS} + a_i$ for each i. At
the central station, a_i, a_j and T^C are known, t_{GPS} is
the chosen reference time, and μ_i and μ_j are received
from the tracked object as measurements. The integers
m_i and m_j are unknown and yield ambiguity as discussed
below. At the receiver, time t_R can be chosen to
align with the first satellite's received code word
boundary. Then $\mu_1 = 0$ by convention and the other
four phases can be sent to the central station. In
this way, the central station can know the individual
phase values as well as their differences. Knowledge
of each phase value at the central station constrains
each unknown associated transmission time to be on a
lattice of time points that have that phase value.

While the above discussion illustrates how the
several satellite propagation time differences can be
deduced from receiver code word phase measurements, as
an alternative, receiver bit phases can be measured.
In this instance, μ_i of equation (8) becomes the bit
phase when γ_i is replaced by β_i, and T_i^C is replaced by
T_i^B. A relationship similar to equation (9) also
holds for bit phases. Finally, in equation (10), m_1
and m_i become the unknown integer number of bit
periods. In either instance, the unknowns m_i and m_j

cause a periodic ambiguity in propagation time difference Δ that must be resolved. This ambiguity has a period of approximately one millisecond for code periods and 20 milliseconds for bit periods.

5   Because each possible propagation time difference value induces a three-dimensional hyperbolic sheet for the railcar location solution, the ambiguity in Δ induces multiple sheets for each value of Δ. On an assumed flat earth, the sheets

10   from just one phase difference form a set of hyperbolas with the positions of satellites i and j as the foci. Phase differences from other satellite pairs induce different hyperbola sets. The only feasible railcar location solutions are those where

15   there is a congruence of one hyperbolic sheet from each participating satellite pair. With ambiguous time differences from four satellites, only a small set of possible joint ambiguity images yield intersecting hyperbolas near the earth's surface, and

20   the set is further reduced as more satellites are used.

       Time-delay difference and satellite location accuracies are such that the location solution regions from each satellite pair are very narrow relative to

25   the ambiguity spacing, as shown in Figure 5. Thus the several ambiguous time delay differences yield a small set of possible railcar locations.

       The use of bit-time differences provides advantages over code-time differences because the

30   former yield a smaller number of possible location solutions. The 20 millisecond period for bit-time differences always yields a location ambiguity spatial period of at least 1500 miles at the earth surface, while for code-time differences the ambiguity spatial

35   period is only 75 miles. This shortest ambiguity

period assumption is derived by assuming the two satellites involved are on the horizon in opposite directions. For railcar tracking applications, car locations will be known *a-priori* to within 1500 miles,

5   so a 1500 mile ambiguity is not a problem. Receiver bit phases, however, are slightly complicated to derive because the satellite's binary data stream is NRZ coded.

Using an NRZ code sequence, a sequence of

10 identical bits has no transitions and bit locations are not visible. However, with GPS data, such sequences are very short, so that bit edges are readily observed. Once a single bit transition has been observed, the receiver bit phase for the chosen

15 time t_R is readily deduced because the code period is observed and there are always 20 code cycles per bit period. Furthermore, each bit boundary coincides with a code word boundary.

In order to solve equation (4) for the railcar

20 receiver location, the propagation time delay differences are first found, as from equation (10). In equation (10), $(m_i - m_j)$ is the unknown integer part of the code or bit period offset between the signals received from satellites i and j. For a given

25 measurement of μ_i and μ_j, equations (10) and (4) yield a different location solution for each value of $(m_i - m_j)$. Conceptually, each integer value of $(m_i - m_j)$ must be tried, and the resulting position solution must be checked against known bounds for

30 validity. In earthbound (e.g., railcar) applications, altitude is a simple bound against which each position solution can be checked. Also, railcar velocities are constrained, so that new locations cannot be extremely different from previous locations.

Most of the ambiguous solutions are at invalid
altitudes, far from the earth's surface. To avoid
wasteful calculation, it is desirable to directly
limit the values of $(m_i - m_j)$ that are used in
5   equation (10). The GPS satellite-earth geometry
constrains each time t_i to be between 58.5 and 79.9
milliseconds (ms). This is true because GPS
satellites orbit at approximately 25×10^3 km above
the earth's center so that the delay from directly
10   overhead is 58.5 ms while the delay from a satellite
on the horizon (nearly 4000 miles farther away) is
79.9 ms. The delay difference between two satellites
is therefore constrained to the interval [-21.4, 21.4]
milliseconds. At the central station, equation (10)
15   is readily used to deduce values of $(m_i - m_j)$ that
satisfy this interval constraint. If code phases are
measured, there are approximately 43 feasible values
of $(m_i - m_j)$ for each measured $(\mu_i - \mu_j)$. Thus there
are 43 values for each Δ_{ij} in equation (4). If bit
20   phases are measured, there are only 2 or 3 feasible
values for each propagation time difference Δ_{ij} and
the resulting list of possible railcar locations will
be much shorter.

To summarize the foregoing object-tracking
25   method ("method 1"), five satellite signals must be
received. Five receiver code word or bit phases are
measured, as are the associated satellite
identification numbers, and these are sent to the
central station. From these measurements a list of
30   feasible railcar locations is determined at the
central station. The basic steps are:

1. Phases μ_1 through μ_5 are measured along with
their corresponding satellite numbers and these data
are sent to the central station. The measured phases
35   can be code word phases in the simplest receiver, or

data-bit phases in a slightly more complex receiver. Bit phase could be specified as code word phase plus an integer number of code words offset from the bit transition.

5   2.   A standard GPS receiver at the central station determines satellite transmission offsets a_1 through a_5 that are valid around the time the receiver measurements are received at the center. Validity of each satellite ephemeris equation is determined for

10   the same time period.

       3.   At the central station, reasonable values for the integer offsets $(m_1 - m_j)$ for j from 2 through 5 are selected, and equation (10) is used to calculate Δ_{1j} for j from 2 through 5.

15   4.   At the central station, an initial value for t_1^T is chosen and equation (5) is used to find corresponding values for t_i^T for i from 2 through 5. The value of t_1^T is constrained such that the transmitted bit or codeword phase at t_1^T has the

20   measured phase, μ_1. The integer m_1 is indirectly specified when choosing a t_1^T that satisfies the above constraint. At the central station, the initial value for transmit time t_1^T may be set to an approximation of the receiver message time t_R, if known. In a railcar-

25   tracking application, time t_R could be known to within several minutes at the central station (without any communication of time values).

       5.   Standard iterative methods are used with equations (1) and (2) in order to solve for the

30   railcar receiver (x, y, z) position and transmission time t_1^T. In equation (2), the ephemeris equation for each satellite is included in the iteration. The last reported location can be used as the initial values for x, y, and z in the iteration.

6. Steps 3 through 5 are then repeated for each feasible combination of integer offsets ($m_1 - m_j$) for j from 2 through 5. This yields a list of potential railcar receiver location solutions.

5   An advantage of the tracking method described above is that requirements for receiver clock accuracy are minimal. Railcar time is not part of the measurement set.

The present invention may alternatively employ a
10   second method ("method 2") for determining location of an object being tracked. The second method is similar to the first method, except that only four satellites are used and the railcar receiver message time t_R must be made known to the central station, (e.g., measured
15   and transmitted to the central station). By using four satellites, only three independent propagation time differences can be obtained from the receiver code word or bit-phase measurements. To determine the railcar location, the time at which these propagation
20   time differences are valid must be known. More specifically, as shown in Figure 4, the transmission times t_i^T, for i from 1 to 4, must be determined so that the satellite position, (associated with the common reception time t_R) can be determined. In a
25   manner similar to the first tracking method, the railcar receiver location is determined from the following three equations:

$$R_2\left(x,y,z,t_1^T - \Delta_{12}\right) - R_1\left(x,y,z,t_1^T\right) = C\Delta_{12} \qquad (11)$$

$$R_3\left(x,y,z,t_1^T - \Delta_{13}\right) - R_1\left(x,y,z,t_1^T\right) = C\Delta_{13}$$

30

$$R_4\left(x,y,z,t_1^T - \Delta_{14}\right) - R_1\left(x,y,z,t_1^T\right) = C\Delta_{14} \quad .$$

In equation 11, the Δ_{1j} terms are derived from the measured code word or bit phases with ambiguities as

in the first tracking method. Also as in the first method, $(t_1^T - \Delta_{1i})$ is the transmission time from the i'th satellite corresponding to reception time t_R. This transmission time determines the satellite

5   location from the ephemeris equations, and the satellite locations are needed to determine the ranges in equations (11). The Δ_{1j} values are known at the central station from the received measurements and equation (10). Furthermore, time t_1^T is related to

10   time t_R by

$$t_1^T = t_R - \tau_1(x, y, z, x_1(t_1^T), y_1(t_1^T), z_1(t_1^T)). \qquad (12)$$

Here τ_1 is the GPS signal propagation delay from satellite 1 and depends, as shown, on location of the

15   object being tracked, and satellite location. The satellite location (x_1, y_1, z_1) depends, in turn, on time t_1^T. Therefore, if time t_R and the satellite ephemeris equations are known, then time t_1^T depends only on the location of the object being tracked. For

20   a given location of the object being tracked, equation (12) can be solved iteratively for time t_1^T. After convergence, the value of t_1^T can be modified to the nearest point of the time grid induced by equations (8) and (9) and the known (measured) value

25   of μ_1 so as to obey the previously mentioned lattice constraint. To speed convergence, this constraint can be applied after each iteration. Equations (11) and (12) together form a system of nonlinear equations with object location (x, y, z) as the only unknowns,

30   and these equations can be solved using standard iterative techniques.

In many railcar tracking applications (e.g., when the railcar is traveling), extreme accuracy is not required. In such cases, t_i^T can be approximated

by $t_R - (79.9 - 58.5)/2$. As stated earlier in the description of the first tracking method, the GPS-signal transmission times (t_i^T) must lie between $t_R - 79.9$ ms and $t_R - 58.5$ ms. This yields a t_1^T

5   uncertainty of 21.4 ms if t_R is known. The satellites travel at approximately 3.49 km per second so that a t_i^T uncertainty of 21.4 ms yields a satellite location (x, y or z) uncertainty of, at most, 74.8 meters, which translates directly to a similar uncertainty in

10   railcar receiver location. This may provide sufficient accuracy for most railcar-tracking applications. If greater accuracy is desired, equation (12) can be included in the iterative solution of equation (11) to determine location of the

15   object being tracked. The initial value for t_1^T can be set equal to t_R and equation (11) iterated to solution for (x, y, z). This result and the initial value for t_1^T can then be used to initialize an iteration for solving equation (12). This yields an improved value

20   for t_1^T which can be used with the previous (x, y, z) solution to initialize another iterative solution of equation (11). This cascade of iterations will rapidly converge to the correct railcar location, subject to the ($m_i - m_j$) induced ambiguities.

25   Small errors in t_R can be tolerated because t_1^T must obey the previously-mentioned lattice constraint. Thus if the received codework or bit phases μ_i are measured at time t_R, but the measured time is actually reported as t_R plus some error ε, the railcar location

30   will be accurately calculated for time t_R if the value of ε is less than one-half of the code word (data-bit) period. If desired, the correct value for t_R can be determined following completion of the iteration using the following equation:

$$t_R = t_1^T + R_1/C. \tag{13}$$

In performing this method of tracking an object, it is assumed that the reception time t_R for the railcar receiver can be accurately measured and used to find the relevant satellite transmission times. This is easily done if the object being tracked includes an accurate clock and its time reading at $t = t_R$ is sent to the central station. Alternatively, time t_R can be determined at the central station by determining the time of data arrival at the central station and using this as a reference. As shown in Figure 6, data transmitted from a GPS satellite at time τ_0 is detected at the railcar receiver at time $\tau_1 = t_R$, is transmitted to the central station at time τ_2, and is received by the central station at time τ_3. The central station maintains an accurate clock so that the value t_R can be determined if both $(\tau_3 - \tau_2)$ and $(\tau_2 - \tau_1)$ are known. The delay $(\tau_2 - \tau_1)$ can be easily recorded by an inexpensive timer located at the railcar receiver and can be transmitted as data to the central station. The communication delay $(\tau_3 - \tau_2)$ is dependent upon the data communication network and may be known at the central station where reception time t_R may then be calculated using the formula:

$$t_R = \tau_3 - (\tau_3 - \tau_2) - (\tau_2 - \tau_1). \tag{14}$$

As indicated in Figure 7, there are some situations in which the data communication may be made via a satellite link. Assuming the use of a geostationary satellite 19 for the data link, transmissions out to and back from the satellite will experience a delay which depends on the locations of central station 16, railcar receiver 14 and satellite 19. This delay will be bounded between

$\emptyset_1 = 2R_1/C$ and $\emptyset_2 = 2(R_1 + R_2)/C$ as can be seen from Figure 7, where C is the speed of light, R_1 is the distance from satellite 19 to the surface of the earth and R_2 is the earth's radius. With R_1 approximately

5   38,623 km and R_2 approximately 6,437 km, the delay uncertainty is approximately 46 ms. During this interval, the GPS satellites move 174 meters at their speed of 3.78 km per second. Thus the railcar locations will have an additional error if this delay

10   uncertainty is not resolved.

If a more accurate railcar location is required, the uncertainty in geostationary satellite delay (due to uncertain railcar location) can be eliminated with an iteration scheme such as that discussed earlier

15   (for the GPS signal delays). Initially, the railcar location is calculated at the central station by assuming a particular feasible value for the communication delay $(\tau_3 - \tau_2)$. With the new railcar location and the known satellite 19 and central

20   station 16 positions, the communication delay is recalculated. This corrected delay is then used in equation (14) to correct the value t_R. The new value of t_R is used, as described earlier, to find a railcar location. This iteration can continue until little

25   change in railcar location is observable.

For accurate results from this approach, the data storage delay $(\tau_2 - \tau_1)$ must be short enough such that the railcar receiver clock yields an accurate storage delay measurement. In a preferred embodiment,

30   the railcar will collect time-difference data approximately every 15 minutes and report these data to the central station hourly. Thus the storage delay $(\tau_2 - \tau_1)$ for the first measurement set could be up to 60 minutes, or 3600 seconds. An inexpensive

35   receiver clock may keep time to one part in one

million, so that a 3.6 ms error may accrue in 3600 seconds. This error is directly reflected in the measured value of t_R. If the residual error in t_R, due to receiver clock drift, is kept to less than one-half of the code word or data-bit period, the iteration method described above will reduce the residual railcar location error to zero.

To summarize this second object-tracking method ("method 2"), four satellite signals must be received. Four receiver code word or bit phases are measured, as are the associated satellite identification numbers and the single measurement time, and these are sent to the central station. The basic steps are:

1. Code word or bit phases μ_1 through μ_4 and their associated satellite numbers are measured at reception time t_R. These data, including the measurement time t_R, are sent to the central station. The bit phase can be specified as code word phase plus an integer number of code words offset from a bit transition. If an accurate clock is not available at the railcar receiver, the data-storage time $(\tau_2 - \tau_1)$ at the railcar receiver is sent instead of the actual measurement time.

2. If storage time is measured at the object being tracked and sent to the central station, then the time of data reception (τ_3) at the central station is determined and used with storage delay $(\tau_2 - \tau_1)$, and with the known bounds on transmission delay between the object being tracked and central station $(\tau_3 - \tau_2)$, to estimate the measured common reception time t_R from equation (14).

3. A standard GPS receiver is used at the central station to determine satellite transmission offsets a_1 through a_4 and the satellite ephemeris equations that are valid near the measured reception

time t_R. Because these parameters change relatively slowly, and because the delay between a GPS satellite and the object being tracked is short, these parameters will be valid at the several satellite

5   transmission times.

4.   At the central station, reasonable values for the integer offsets, $(m_1 - m_j)$ for j from 2 through 4 are selected, in view of limitations on these offsets that are induced by satellite-earth

10 geometry, prior object location, object velocity limits, etc. Equation (10) is used to calculate propagation time difference Δ_{1j} for j from 2 through 4.

5.   At the central station, an initial value

15 for time t_1^T is chosen based on μ_1, and on limitations on the communication delay $(\tau_3 - \tau_2)$ and bounds on the GPS signal travel delays (τ_j). An effective simple initial value is $t_1^T = t_R$.

6.   Equation (5) is then used to calculate

20 corresponding values for t_i^T for i from 2 through 4.

7.   Standard iterative methods are then used to solve equation (11) for railcar receiver location (x,y,z). Because the values t_i^T are fixed, the ephemeris equations are evaluated only once during

25 this iteration.

8.   For higher accuracy, the new (x, y, z) result is used with equation (12) to iteratively solve for an improved value of t_1^T. This can be done either after step 7 has converged, or after each iteration of

30 step 7.

9.   Steps 6 through 8 are repeated, terminating after step 7 if the new position (x, y, z) is substantially unchanged.

10.   Steps 4 through 9 are repeated for each

35 feasible combination of integer offsets, $(m_1 - m_j)$ for

30

j from 2 through 4. This yields a list of potential railcar location solutions.

An advantage of this second method of object tracking is that only four satellite signals must be
5 received. Furthermore, the iteration for finding railcar location is less time-consuming because the search for the correct GPS transmission times is substantially eliminated.

For some communication methods, the
10 communication delay time cannot be determined with sufficient accuracy. In such cases, other methods for determining receiver and transmission times must be used. One approach is to utilize a unique mark (unique over a sufficient period) in any one GPS
15 satellite's data stream as a time reference at the tracked object, and to measure reception or receiver time t_R relative to this received mark. Because the mark is unique, it can be found in the GPS signal received at the central station and its transmission
20 time can be determined accordingly. Hence the transmission time associated with reception time t_R can be found by adding the measured offset to the mark time. All other satellite transmission times t_i^T can then be found from the known offsets a_j at the central
25 station. Utilizing equations (11) and (13), the railcar receiver locations and associated receiver times are calculated.

The GPS telemetry-word preamble (TWP) is a specific eight-bit sequence (10001011) that is
30 transmitted at the beginning of every six-second subframe from each satellite and is a standard synchronization mark. This sequence cannot be falsely replicated by any prefix or postfix of up to six bits in length. If a short periodic receiver window is
35 synchronized with the TWP from one of the satellites

a signal event such as

whose data is to be processed, and this window is used to occasionally "awaken" or activate the railcar receiver for TWP-synchronized GPS signal processing, little or no extra power will be required at the

5 railcar receiver to support learning the transmission times at the central station. This TWP windowing scheme is useful if the uncertainty in satellite transmission times is less than six seconds. Initial window synchronization may require up to a full six

10 seconds of GPS data processing to ensure TWP acquisition but, once acquired, the window can easily be tracked by noting the position of each TWP in its surrounding window and altering the window timing to keep the TWP centered. With inexpensive clocks at the

15 railcar receiver, the window can drift on the order of only 3.6 ms per hour. If the signal TWP region is also used for the time-difference processing, then the window can drift only on the order of 3.6/4 ms over the 15 minute inter-measurement interval. Since the

20 TWP sequence is unique within ±6 bit periods (120 ms), use of a 100 ms window ensures that the TWP will not be missed or falsely recognized.

If the transmission delay to the central station has uncertainty greater than six seconds, the TWP

25 windowing scheme can be augmented with GPS time-stamp decoding at the receiver. The GPS time stamp is encoded in the data stream at a fixed short delay from the TWP word. The TWP window can be used to enable time-stamp decoding, and the time stamp can be sent to

30 the central station as an estimate of the receiver time t_R. As an alternative, time t_R can be chosen at the railcar receiver to coincide with the TWP word boundary on satellite channel number 1, and the following time stamp can be decoded and sent to the

35 central station. The correct value for time t_1^T is

then easily found at the central station as the value of the time stamp prior to that from the receiver.

The above railcar receiver windowing scheme need be implemented only on one of the satellite signals in order to determine receiver time t_R. However, if a separate TWP receiver window is formed, respectively, for each satellite signal, then all time-delay ambiguities associated with code or bit periods are readily resolved by noting the TWP-relative time at the end of the correlation process for each signal. This simplifies processing at the central station at the expense of extra window processing and receiver "on" time at the railcar receiver.

A further method for determining time is to broadcast time signals via a separate channel accessible to the railcar receivers. For example, time signals may be transmitted over a separate geostationary satellite link on a one-second grid or smaller, thereby easing railcar receiver clock accuracy requirements. This method results in a railcar-location dependent delay from the central station to the railcar receiver. The delay can be accounted for by using iterations in a manner similar to that described above.

Figure 8 illustrates a system for evaluating GPS-based localization algorithms for low power tracking applications. The system includes a standard GPS hardware unit 22 for receiving GPS signals and developing standard GPS navigation solutions for reference, and a data interface unit 24 and computer workstation 26 for generating GPS navigation solutions using the reduced-power GPS methods described herein. Standard GPS hardware unit 22 uses a commercially available multi-channel GPS receiver and GPS signal processor to develop standard navigation solutions.

Data interface unit 24 collects intermediate GPS signal information from hardware unit 22 (e.g., demodulated but unprocessed GPS data streams), performs some data processing (e.g., calculate

5 relative bit phases of the different GPS signals), and passes the results to computer workstation 26. The data interface unit also collects decoded GPS almanac, ephemeris, and clock correction data from the hardware unit and passes these to the workstation. At the

10 workstation, the various reduced-power GPS tracking algorithms are developed using the commercially available Matlab programming language. Matlab is available from The MathWorks, Inc., Natick, Mass. The tracked unit (railcar) and central-station functions

15 are performed separately in the computer workstation.

While only certain preferred features of the invention have been illustrated and described, many modifications and changes will occur to those skilled in the art. It is, therefore, to be understood that

20 the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

Attached hereto, as Appendix A, is a source code listing which may be utilized by the central station

25 to calculate the location of the object being tracked, pursuant to method 1 herein.